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Development of Rating Curve Estimators for Suspended-Sediment Concentration and Transport in the C-51 Canal Based on Surrogate Technology, Palm Beach County, Florida, 2004-05

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By A.C. Lietz and Elizabeth A. Debiak

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U.S. Department of the Interior
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Conversion Factors, Abbreviations, Acronyms, and Datum

Multiply	By	To obtain
inch (in.)	25.40	millimeter (mm)
inch per year (in/yr)	2.54	centimeter per year (cm/yr)
foot (ft)	0.3048	meter (m)
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
acre	0.4047	hectare (ha)
gallon (gal)	3.785	liter (L)

FNU	formazin nephelometric unit
mg/L	milligram per liter
µS/cm	microsiemens per centimeter at 25 degrees Celsius

EWI	equal-width increment
FDEP	Florida Department of Environmental Protection
MDL	method detection limit
NASQAN	National Stream Quality Accounting Network
PQL	practical quantitation limit
RPD	Relative percentage difference
SFWMD	South Florida Water Management District
SSC	suspended-sediment concentration
USGS	U.S. Geological Survey

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 1929). Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Development of Rating Curve Estimators for Suspended-Sediment Concentration and Transport in the C-51 Canal Based on Surrogate Technology, Palm Beach County, Florida, 2004-05

By A.C. Lietz and Elizabeth A. Debiak

Abstract

The Lake Worth Lagoon watershed encompasses about 450 square miles in Palm Beach County, and represents one of the most important estuarine areas in Florida. Anthropogenic activities beginning in the late 19th century and continuing through today have adversely affected the natural resources and aquatic biota of the lagoon. A major concern is the large deposition of muck sediment that has had a deleterious effect on seagrass growth. The major cause of these sediment deposits most likely is due to stormwater heavily laden with fluvial sediment, discharging through the S-155 control structure on the West Palm Beach (C-51) Canal.

To address this problem, the U.S. Geological Survey and the Palm Beach County Department of Environmental Resource Management engaged in a joint partnership utilizing surrogate technology to develop rating curve estimators based on the relation between suspended sediment and different explanatory variables, including turbidity and discharge. To fulfill this objective, a continuous, instream water-quality monitoring station that records turbidity data in real time was installed upstream of structure S-155. Point samples were collected near the probe, and depth- and width-integrated samples were collected along the stream cross section. The water samples were collected over a range of seasonal and hydrologic conditions (from 2- to 85-percent exceedance on the flow-duration curve) and analyzed at a U.S. Geological Survey sediment laboratory. Four rating curve estimators were developed based on simple linear and multiple linear regression analyses to estimate suspended-sediment concentrations upstream of structure S-155 using the logarithms of turbidity, turbidity and discharge, and discharge. The coefficients of determination (R^2) ranged from 0.75 to 0.90.

Cross-sectional water-quality surveys were made at three verticals in the stream cross section during various seasonal and hydrologic conditions to assess water-quality homogeneity in the stream. Results indicated a range of concentration differences of 18 to 60, 11 to 62, 9 to 33, and 18 to 31 percent for the surveys made on December 4, 2003, March 15, 2004, September 14, 2004, and November 7, 2004, respectively.

Quality-assurance samples were collected as part of this study and included equipment blanks, field blanks, and duplicate samples. Relative percent differences between duplicate samples collected at the probe and cross section (4.6 and 0.0 percent, respectively) were within Florida Department of Environmental Protection standards.

The nonparametric Wilcoxon signed-rank test was used with hydrologic data to statistically compare: (1) measured and estimated suspended-sediment concentrations; (2) suspended-sediment concentrations estimated at the probe and at the cross section; (3) estimated suspended-sediment concentrations at the cross section using different explanatory variables; and (4) estimated suspended-sediment loads at the cross section using different explanatory variables. The suspended-sediment concentrations at the stream cross section

were estimated from continuous turbidity and discharge data collected during the 2004 water year (October 2003 to September 2004). Statistically significant differences at the 95-percent confidence level (p-value less than 0.025) occurred for all suspended-sediment concentrations estimated at the cross section between turbidity and discharge, between turbidity and turbidity and discharge, and between discharge and turbidity and discharge. Estimated suspended-sediment loads at the cross section also were statistically significant between these same explanatory variables. Additionally, statistically significant differences occurred for suspended-sediment concentrations estimated from turbidity at the probe and at the cross section and for suspended-sediment concentrations estimated from turbidity at the probe and from turbidity and discharge at the cross section. In accordance with these results, the logarithm of both turbidity and discharge as explanatory variables is the best estimator for computing suspended-sediment concentrations and loads at the stream cross section.

Introduction

The Lake Worth Lagoon watershed, one of the largest estuarine systems in Florida, occupies more than 450 mi^2 in Palm Beach County and drains into the Lake Worth and South Lake Worth Inlets (fig. 1). The lagoon historically was a freshwater lake separated from the Atlantic Ocean by a barrier island to the east. Beginning in the late 1800s and continuing through today, the lagoon has been adversely affected by anthropogenic activities; heavy urbanization has resulted in a loss of wetlands, lowered water tables, increased watershed imperviousness, and changes in historical runoff patterns. As a consequence, the Florida Department of Environmental Protection (FDEP) and Palm Beach County formed the Lake Worth Lagoon Ecosystem Management Area team in January 1997 to identify goals and objectives for restoring and preserving the lagoon ecosystem. The team gathered input from numerous government agencies, business and industrial firms, nonprofit groups, and others all concerned with the overall health and well being of the lagoon.

One of the most important indicators of estuarine system health is the presence of seagrasses. In the Lake Worth Lagoon watershed, a varied decrease in seagrass bed abundance has occurred over the last five decades. Seagrasses are beneficial to the estuarine community because of their ability to maintain water clarity, stabilize bottom sediments, provide habitat for a variety of aquatic life, and supply food for marine animals. Previous seagrass surveys have estimated that 4,271, 161, and 2,010 acres of seagrass existed in the lagoon during 1940, 1975, and 1990, respectively (South Florida Water Management District, 2003).

The gradual accumulation of fine-grained silt and clay-enriched organic sediments has greatly affected seagrass in the Lake Worth Lagoon. These sediments have resulted in increased turbidity and reduced light penetration, and have accumulated at an estimated rate of 0.1 to 0.9 cm/yr (0.039 to 0.35 in/yr) over the last 20 years (South Florida Water Management District, written comm., 2004). A large volume of this suspended material most likely results from nonpoint source stormwater discharges, principally from the C-51 Canal at structure S-155 (fig. 1). To mitigate this problem, future plans call for: (1) diverting some discharge from the C-51 Canal to Stormwater Treatment Area 1E (STA1E) in east-central Palm Beach County, and (2) examining the transport of sediment in the canal. As a consequence, the U.S. Geological Survey (USGS), in cooperation with the Palm Beach County Department of Environmental Resources Management, recently conducted a study to document suspended-sediment concentration (SSC) and transport in the C-51 Canal based on the use of surrogate technology and the development of rating curve estimators.

Purpose and Scope

The purpose of this report is to document the development of rating curve estimators or regression models for the estimation of SSC and suspended-sediment transport in the C-51 Canal by employing simple and multiple linear regression analysis methods. Historical water-quality data and discharge data collected at structure S-155 along the C-51 Canal are summarized, including procedures for discharge computation and laboratory analysis. The field and laboratory quality-assurance protocols (adapted for the study) are documented, as well as quality-assurance results for equipment blanks and duplicate samples and their relation to FDEP guidelines.

Simple linear (ordinary least squares) and multiple linear regression analyses are used to develop rating curve estimators for concentrations and loads of suspended sediment based on continuous turbidity and discharge data for the 2004 water year (October 2003 to September 2004). Residuals analysis is used in conjunction with p-values and coefficients of determination (R^2) to evaluate models based on simple linear regression; Mallow's *Cp* statistic also is used to evaluate models based on multiple linear regression. Graphs that compare SSC residuals and estimated SSC values, response variables and estimated SSC values, and SSC residuals and quantiles are presented for the best models. The nonparametric Wilcoxon signed-rank test is used to compare: (1) measured and estimated concentrations of suspended sediment; (2) estimated concentrations of suspended sediment at the probe and the cross section; (3) estimated concentrations of suspended sediment at the cross section between different explanatory variables; and (4) estimated suspended-sediment loads at the cross section between different explanatory variables. The concentrations and loads of suspended sediment are estimated from turbidity and discharge data. The fitted concentrations of suspended sediment from each of the rating curve estimators and their upper and lower 95-percent confidence limits also are described in this report.

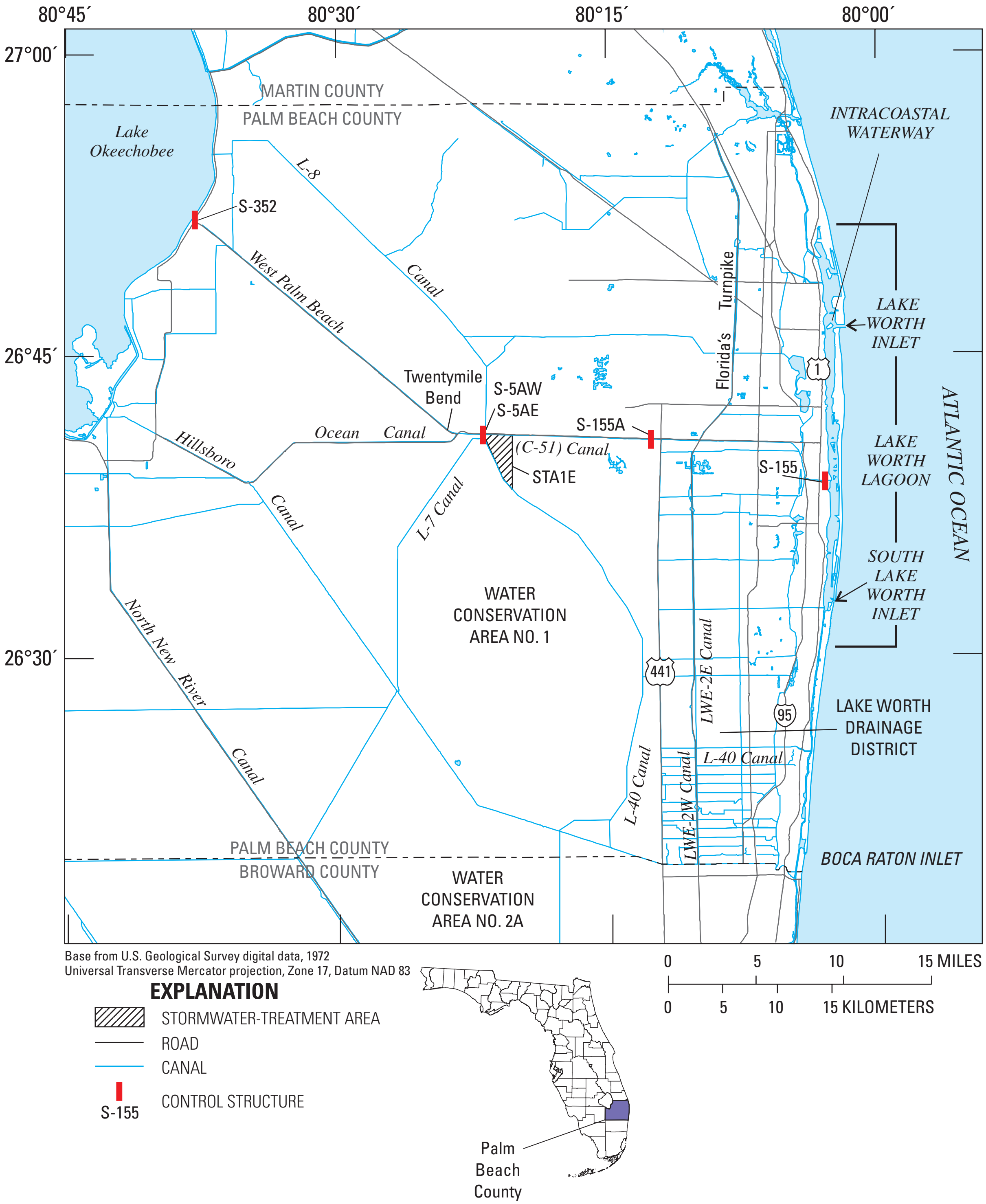

Figure 1. Location of the Lake Worth Lagoon, stormwater-treatment area, and major control structures along the C-51 Canal in Palm Beach County, Florida.

Description of Study Site and Canal System

The study site is located along the C-51 Canal, about 1,000 ft upstream of structure S-155 in eastern Palm Beach County, Florida (fig. 1). Structure S-155 is about 0.5 mi upstream of the Lake Worth Lagoon, which is part of the Intracoastal Waterway. Land-surface elevation near the study site ranges from about 15 to 20 ft above NGVD 1929.

The C-51 Canal is about 42 mi in length, and extends from structure S-352 at the southeastern shore of Lake Okeechobee to structure S-155 (fig. 1). The canal is intersected by the Ocean Canal (also known as Cross Canal, Cross Cut Canal, and Levee 13) at Twenty Mile Bend and by the Levee 8 and 40 (L-8 and L-40) Canals at structures S-5AW and S-5AE, respectively. Together with these associated control structures, the C-51 Canal serves several purposes. During the winter and spring, water is discharged from structure S-352 to meet local agricultural needs and provide irrigation to the Lake Worth Drainage District. Water Conservation Area No. 1 receives water from the C-51 Canal by means of discharge through structures S-5AW and S-5AE. Under current plans, some discharge will be diverted from the western watershed of the C-51 Canal basin to Stormwater Treatment Area 1E (fig. 1, STA1E).

Discharge of excess water during the wet season or during flood conditions and the retardation of saltwater intrusion during the dry season are accomplished by opening or closing the gates at structure S-155 as needed. This gated spillway consists of three lift gates that automatically open according to programmed criteria, but may be manually overridden if necessary. The gates are closed much of the year, particularly during the dry season.

Previous Studies

Many earlier studies have used surrogate technology to develop rating curve estimators or regression models. In southern Florida, Patino (1996) investigated the feasibility of using acoustic attenuation for estimating highly organic suspended-solids concentrations at structure G-88 in the Everglades Agricultural Area in northwestern Broward County. Patino (2004) also documented the application of both acoustic and optic methods for estimating suspended-solids concentrations in the St. Lucie River Estuary. Christiansen and others (2000) used real-time water-quality monitoring and regression analysis to estimate constituent concentrations, loads, and yields in the Little Arkansas River in south-central Kansas. Regression models were developed for a number of constituents including alkalinity, dissolved solids, total suspended solids, chloride, sulfate, atrazine, and fecal coliform bacteria. Christiansen and others (2001a) also used real-time water-quality monitoring and regression analysis to estimate nutrient and bacteria concentrations in selected streams in Kansas. In another study, Christiansen and others (2001b) used continuous turbidity monitoring and regression analysis to estimate total suspended solids and fecal coliform bacteria loads in real time at the Little Arkansas River. Runner (2003) described turbidity and estimated sediment loads at Deer Creek, east of Leland, Mississippi. Schoellhamer (2001) described continuous monitoring of suspended sediment in rivers employing optical sensors.

Acknowledgments

The authors graciously acknowledge the assistance of George Hwa and the staff in the control room of the South Florida Water Management District (SFWMD). These invaluable employees maintained gate openings to facilitate the collection of water samples.

Data Collection and Processing Methods

Discharge data used for this study was computed as part of an ongoing data-collection effort conducted jointly by the USGS and SFWMD. A continuous instream water-quality monitoring device was used for this study to collect continuous turbidity data upstream of structure S-155. Suspended-sediment samples also were collected near the turbidity probe and at the stream cross section. Data from the monitoring device and samples were used to develop relations between SSC and explanatory variables, such as turbidity and discharge, at these locations. Cross-sectional water-quality surveys were conducted periodically to document the degree of water-quality homogeneity in the stream cross section. Water samples were analyzed at the USGS Kentucky Water Science Center Sediment Laboratory in Louisville, Kentucky. The subsequent sections describe historical data-collection efforts, discharge computation at structure S-155, turbidity data collection, suspended-sediment sample collection and processing, cross-sectional water-quality surveys, laboratory methods used to analyze the samples, and quality-assurance procedures conducted as part of the study.

Historical Data Collection at the C-51 Canal

The USGS has been computing discharge data at structure S-155 since 1939; the highest mean daily discharge occurred during Hurricane Irene on October 16, 1999, with an estimated discharge of 8,540 ft^3/s. Water-quality data also have been collected at the C-51 Canal upstream of structure S-155 since 1939. Major inorganic constituents and nitrogen species were sampled from December 1939 to September 1953 (table 1). From May 1967 to September 1973, sampling efforts were expanded to include the phosphorus species, selected metals, and field constituents given in table 1. From October 1974 to September 1986, the C-51 Canal was included in the USGS National Stream Quality Accounting Network (NASQAN). This network consisted of almost 500 sampling stations

Table 1. Water-quality data collected at the C-51 Canal from 1939 to 1986.

Constituent	Data-collection period				
	December 1939 to September 1953	May 1967 to September 1973	October 1974 to September 1986	November 1974 to September 1986	May 1978 to September 1986
Laboratory Constituents					
Major inorganics	✓	✓	✓		
Color	✓	✓			
Alkalinity	✓	✓	✓		
Hardness	✓	✓	✓		
Total dissolved solids	✓	✓	✓		
Nitrogen species	✓	✓	✓		
Phosphorus species		✓	✓		
Total organic carbon			✓		
Trace metals			✓		
Selected metals		✓			
Suspended sediment				✓	
Turbidity					✓
Field Constituents					
pH		✓	✓		
Specific conductance		✓	✓		
Dissolved oxygen		✓	✓		
Temperature		✓	✓		
Biological Constituents					
Total coliform			✓		
Fecal coliform			✓		
Phytoplankton			✓		
Periphyton			✓		

located downstream of major drainage basins within the United States; these stations were used to detect regional trends in water quality. Under this program, sampling efforts at the C-51 Canal upstream of structure S-155 were further expanded to include biological constituents (table 1).

Because the present study uses turbidity data to develop a rating based on the suspended sediment and turbidity relation, a summary of the historical turbidity and suspended-sediment data collected at structure S-155 is of special importance. Turbidity data were collected from May 1978 to September 1986, and suspended-sediment data were collected from November 1974 to September 1986. A summary of the historical turbidity (in milligrams per liter) and suspended-sediment (in formazin nephelometric units) data collected upstream of structure S-155 is given below:

Discharge and Real-Time Turbidity Data

Computation of discharge through structure S-155 is accomplished using hydraulic relations between upstream stage (water level), downstream stage, and three gate openings. For the 2004 water year, upstream stage and downstream stage were recorded by an electronic data logger every 15 minutes, and data were downloaded on a monthly basis by USGS personnel. Stage data also were collected at 15-minute intervals by the SFWMD. All USGS data are stored in the USGS National Water Information System database. Annual mean daily discharge, highest mean daily discharge, and lowest mean daily discharge for the 2004 water year were 460, 5,230, and 0 ft^3/s, respectively (fig. 2A).

Constituent	Sample size	Maximum	Minimum	Mean	95th percentile	75th percentile	Median	25th percentile	5th percentile
Turbidity	54	44	0.2	3.4	8.6	4.0	2.0	1.0	0.4
Suspended sediment	64	80	1.0	6.7	21	6.0	4.0	3.0	1.0

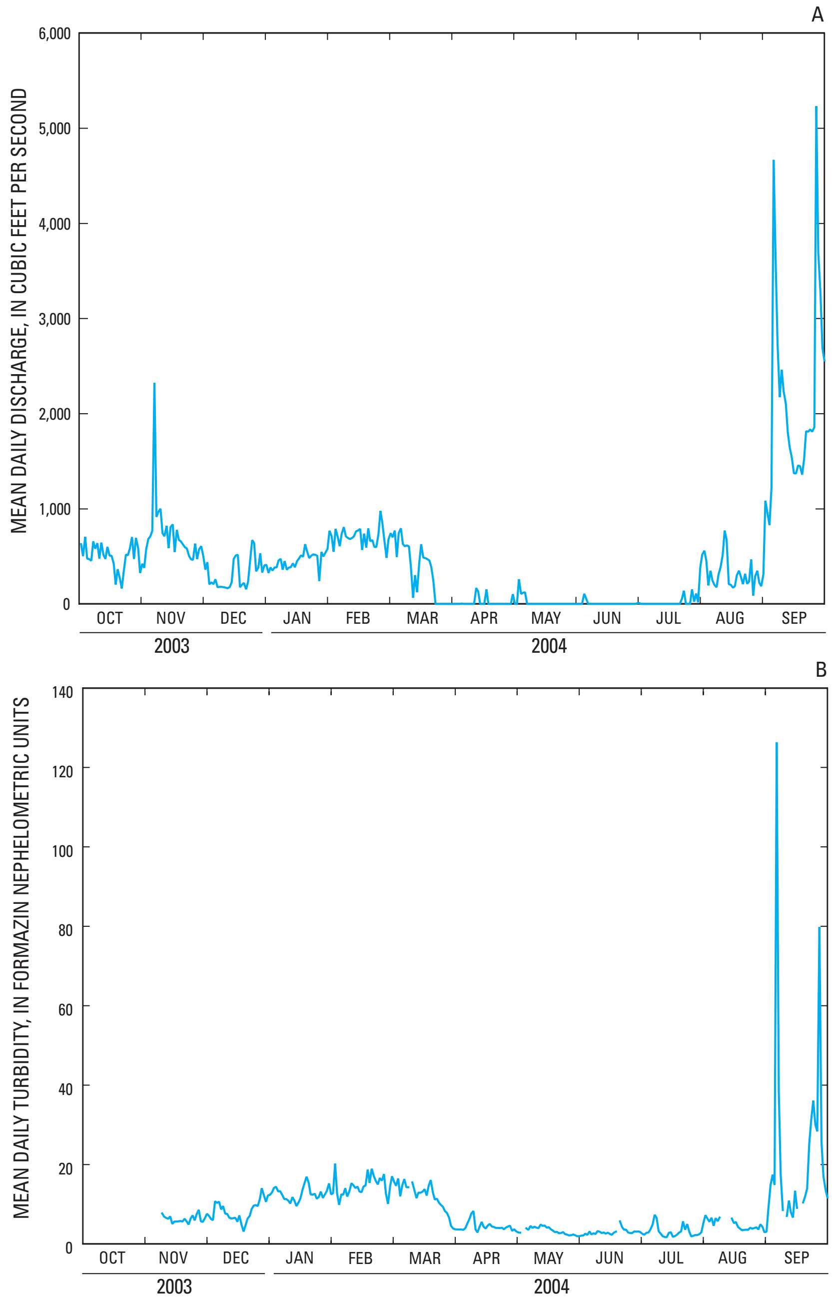

Figure 2. Mean daily (A) discharge and (B) turbidity for the 2004 water year.

Upstream stage is regulated by the S-155 vertical lift gates, as previously mentioned, and downstream stage is controlled by the tide. The USGS computes discharge based on gate ratings that correspond to three different flow regimes—free weir, free orifice (most common), and submerged orifice. Equation coefficients are calibrated and verified by making discharge measurements with an Acoustic Doppler Current Profiler and AA Price Current Meter. Collins (1977) explains how the various hydraulic relations were developed.

The USGS DAMFLO.2 program (Sanders and Feaster, 2004) is used to compute discharge at structure S-155. As input, this program uses upstream and downstream stage, both referenced to the gate sill elevation, and the opening at each of the three gates. The hydraulic regime and discharge are determined using the equations listed in table 2. Discharge through structure S-155 is usually not constant for an entire day and can typically vary daily during the wet season by as much as 1,000 ft^3/s. The mean daily discharge value is a geometric average of the instantaneous 15-minute discharge data collected for the entire day.

Table 2. Flow regimes for structure S-155 along the C-51 Canal and associated hydraulic conditions and flow equations.

[h_g, vertical gate opening; h_1, static headwater elevation reference to gate sill; h_3, static tailwater elevation referenced to gate sill; Q, discharge; C, free orifice flow coefficient; B, lateral width of gate; g, acceleration due to gravity; C_{gs}, submerged orifice flow coefficient; C_w, free weir flow coefficient, g, acceleration due to gravity]

Flow regime	Hydraulic condition relations	Flow equation
Free orifice	$h_g < 2/3h_1$ $h_3 < h_g$	$Q = Ch_gB\ (2gh_1)^{1/2}$
Submerged orifice	$h_g < 2/3h_1$ $h_3 \geq h_g$	$Q = C_{gs}h_3B\ \left(2g\ (h_1 - h_3)\right)^{1/2}$
Free weir	$h_g > 2/3h_1$ $h_3/h_1 < 0.6$	$Q = C_wBh_1^{3/2}$

Turbidity is a measure of the reduction in transparency of a solution primarily caused by suspended material, and is determined by measuring the optical properties of a solution that cause light to be scattered and attenuated. As the intensity of scattered or attenuated light increases, so does turbidity. The light source commonly used is a light emitting diode, and the detector is a photodiode with high sensitivity. Software is used to process sensor output, which is provided in formazin nephelometric units (YSI Incorporated, 2002).

For the current study, turbidity data were collected using a YSI 600 Optical Monitoring System consisting of a 6136 turbidity probe and sensor. The probe was vertically suspended at the end of a 20-ft dock on the south side of the C-51 Canal about 100 ft upstream of the US Highway 1 bridge, or about 1,000 ft upstream of structure S-155 (fig. 3). During average stage conditions, the probe was about 20 ft from shore and about 2.5 ft below the water surface. The canal is 150 ft wide and, on average, about 18 ft deep. Turbidity was measured every 15 minutes and recorded by a Handar 570 data-collection platform. Data were relayed by satellite to the USGS Miami office every 4 hours.

The turbidity sensor has a published accuracy of +5 percent or 2 FNUs, whichever is greater. The probe was serviced at least once a month, which involved cleaning and checking for calibration drift and error caused by fouling. Corrections for biological fouling were rarely needed because of the freshwater environment, and corrections for sediment buildup were rarely needed because an automatic wiper cleaned the optics before every reading. The accuracy of the probe was checked with three standards, and any corrections that needed to be applied were based on differences between the standard and the turbidity probe reading. Corrections were typically prorated between visits. Mean daily turbidity data for the 2004 water year are shown in figure 2B. The maximum and minimum daily turbidity measured for the period were 130 and 1.7 FNUs, respectively.

Suspended-Sediment Sample Collection

Suspended sediment is defined as material that is kept in suspension by the upward components of turbulent currents or that exists in suspension as a colloid. The SSC is the velocity-weighted concentration of suspended sediment in the sampled zone (from the water surface to a point about 0.3 ft above the streambed), expressed as milligrams of dry sediment per liter of water-sediment mixture (Price and others, 2002).

For the current study, two types of water samples were collected at the C-51 Canal during each sampling event: point samples (at the turbidity probe) and cross-sectional samples (at the bridge). Water samples at the probe were collected using a Van Dorn sampler (fig. 4), which consists of a chamber that can be remotely closed to contain a sample at the desired depth. Depth and width-integrated samples also were collected using the equal-width-increment (EWI) method at the stream cross section upstream of structure S-155 at the U.S. Highway 1 bridge (fig. 5). By this method, the stream cross section was divided into equal intervals, and a sampling vertical was established in the center of each interval. Three to five intervals in the cross section were usually sufficient to collect a representative water sample.

Figure 3. Turbidity probe installation upstream of structure S-155.

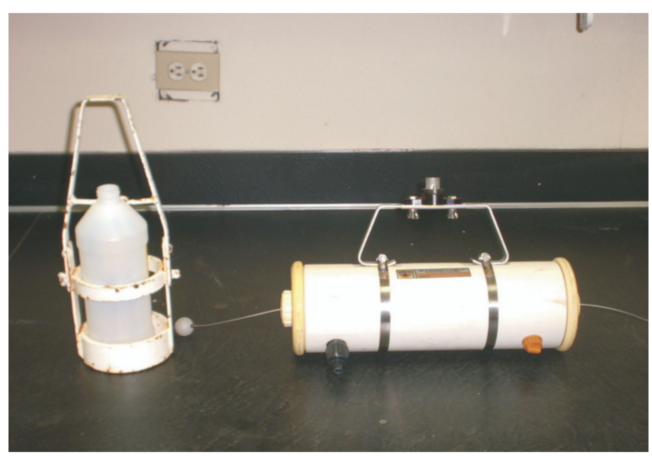

Figure 4. Weighted-bottle (left) and Van Dorn (right) samplers.

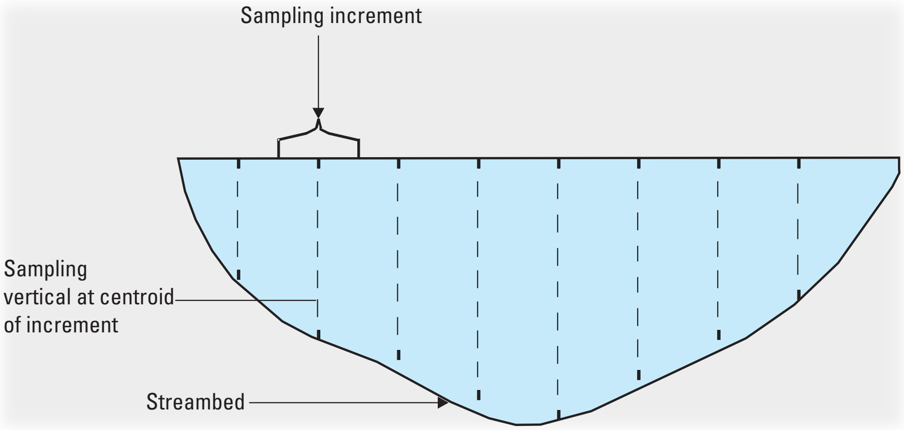

Figure 5. Process for collecting depth and width-integrated samples by way of the equal-width-increment method.

A weighted bottle may be used for EWI sampling in slow moving streams where water velocity is usually less than 2.0 ft/s and water depths range from 3 to 15 ft. Use of a weighted-bottle sampler does not result in the collection of an isokinetic sample; however, a representative water sample can be collected if a stream is shallow and water quality is generally homogeneous in the stream cross section. The weighted-bottle method, which usually is appropriate for most streams in southern Florida, was used to collect cross-section samples for the current study. In this case, a properly weighted metal device containing a 1-L (0.26-gal) polyethylene sample bottle was suspended by a rope at the desired sampling location and lowered and raised at a constant transit rate so the bottle was not overfilled when returned to the surface. This same vertical transit rate was maintained throughout each vertical profile. A list of all water samples collected at the probe and stream cross section used in development of the rating curve estimators is given in table 3.

Water samples were shipped to the USGS Kentucky Water Science Center Sediment Laboratory for composition and analysis of SSC and sand/fine separation. Suspended-sediment analytical results were entered into the USGS National Water Information System database using options available in the QWDATA entry and retrieval system. Water samples collected at the probe and stream cross section were compared to ascertain the accuracy of probe samples in representing SSC in the stream cross section. The descriptive statistics for SSC samples collected at the cross section by means of the EWI method and the percentage of material less than 0.063 mm (0.0025 in.) in diameter are as follows:

Constituent	Sample size	Maximum	Minimum	Mean	95th percentile	75th percentile	Median	25th percentile	5th percentile
All diameters, in mg/L	21	30	5	12.1	51.6	16.5	9.0	6.0	5.0
Percentage with diameter less than 0.063 mm	21	98	36	87	98	97	94	83.5	37.7

The SSC concentrations in water at the cross section ranged from 5 to 30 mg/L, with a mean of 12.1 mg/L. The percentage of material less than 0.063 mm (0.0025 in.) in diameter ranged from 36 to 98 percent, with a mean of 87 percent. The USGS generally classifies suspended material with a particle diameter of 0.0024 to 0.004 mm (0.00009 to 0.00016 in.) as clay, 0.004 to 0.062 mm (0.00016 to 0.0024 in.) as silt, and 0.062 to 2 mm (0.0024 to 0.079 in.) as sand (Hem, 1985). Therefore, 36 to 98 percent of the suspended-sediment samples collected from the C-51 Canal were classified either as clay or silt.

Table 3. List of samples collected at a cross section and probe used in the development of estimators.

[SSC_{ewi}, suspended-sediment concentration from cross-section samples; $Turb_{ewi}$, turbidity reading during cross-section sampling; Q_{ewi}, discharge during cross-section sampling; mm, millimeter; SSC_p, suspended-sediment concentration at probe; $Turb_p$, turbidity reading during probe sampling; Q_p, discharge during probe sampling; BD, bad data; —, missing data]

Date	SSC_{ewi}	$Turb_{ewi}$	Q_{ewi}	Percent finer than 0.063 mm	SSC_p	$Turb_p$	Q_p
11/13/03	6	4.2	408	89	5	4.6	692
11/17/03	6	6.5	871	98	9	6.5	871
02/10/04	16	13.4	857	97	12	15.1	857
02/26/04	15	15.8	955	97	19	15.8	955
03/15/04	9	10.4	246	94	11	10.4	246
04/12/04	8	4.6	1,010	36	4	4.2	1,010
07/27/04	5	2.9	735	53	3	2.6	738
08/02/04	7	4.6	226	77	BD	BD	226
08/04/04	6	6.2	678	89	10	6.2	678
08/06/04	6	4.8	0	82	6	5.2	0
08/13/04	7	6.5	718	94	6	6.5	717
08/14/04	8	6.2	696	84	6	6.2	696
08/27/04	5	4.1	481	83	4	4.1	481
09/07/04	25	18.1	2,690	96	19	18.1	2,690
09/08/04	16	7.8	2,180	97	—	—	2,180
09/22/04	17	24.2	1,920	98	9	24.4	1,920
09/27/04	30	23.1	4,060	94	BD	BD	4,060
10/13/04	20	14.0	1,499	97	14	14.0	1,499
10/27/04	BD	BD	869	95	23	47.0	869
11/09/04	14	24.0	267	93	13	24.0	267
12/15/04	54	78.0	584	95	58	76.0	584

A goal of this study was to collect water samples representative of the C-51 Canal cross section over a wide range of flow conditions. Therefore, the rating curves that were developed accurately represent concentrations and loads over the range of discharge and hydrologic conditions normally found in the C-51 Canal. In accordance with this goal, water samples were collected from an approximate range of 2- to 85-percent exceedance on the flow-duration curve at structure S-155 in the C-51 Canal (fig. 6). This graph shows that sample collection events during the current study were representative of historical flow conditions.

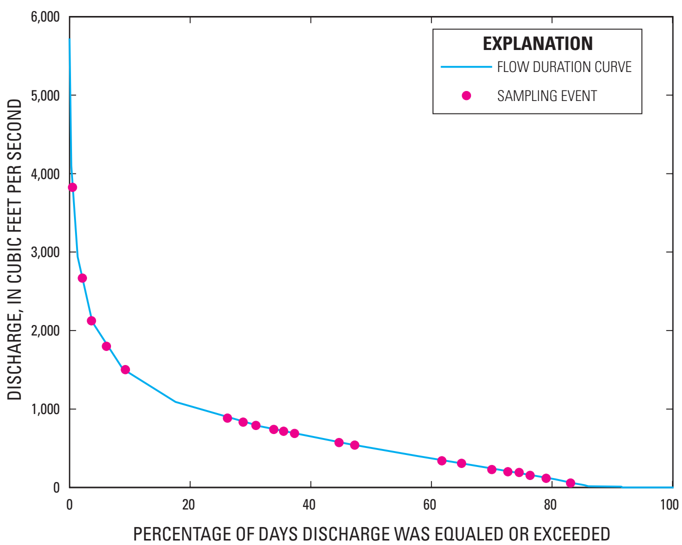

Figure 6. Flow-duration curve showing discharge during sampling events at structure S-155 along the C-51 Canal.

Cross-Sectional Water-Quality Surveys

As previously mentioned, the weighted-bottle sampling method is commonly used in southern Florida streams, and is most appropriate when stream velocity is less than 2.0 ft/s and the water-quality constituents exhibit a uniform overall distribution in the cross section. To verify that this sampling method was appropriate for the current study, the degree of homogeneity in the water column was documented, and cross-sectional water-quality surveys of SSC, pH, specific conductance, water temperature, and turbidity were made in the stream cross section. Four cross-sectional SSC surveys and two cross-sectional surveys of pH, specific conductance, water temperature, and turbidity were made during the project data-collection effort. Cross-sectional SSC surveys were made on December 4, 2003, March 15, 2004, September 14, 2004, and November 9, 2004, with mean daily discharges of 227, 425, 1,530, and 267 ft^3/s, respectively (fig. 7). Surveys were made from three verticals in the cross section at distances of 24, 59, and 86 ft from the right bank looking downstream. Survey results are given below:

Survey date	Greatest percentage variation in SSC (at distance shown from right bank, looking downstream)		
	24 feet	59 feet	86 feet
12/04/2003	18	60	45
03/15/2004	11	22	62
09/14/2004	11	33	9
11/09/2004	31	21	18

Variations in SSC of 10 percent or more commonly occur in high-velocity streams in northern states, and variations exceeding 100 percent are not uncommon for these streams, especially for the coarser (greater than 0.062 mm or 0.0024 in.) material (J.R. Gray, U.S. Geological Survey, written commun., 2005).

Cross-sectional surveys of pH, specific conductance, water temperature, and turbidity were made on March 11, 2004, and September 14, 2004, using a Hydrolab multiparameter recording instrument. For the March 11th survey, pH varied from 7.3 to 7.6, specific conductance varied from 679 to 682 µS/cm, temperature varied from 21.6 to 22.1 °C, and turbidity varied from 14 to 20 FNUs. For the September 14th survey, pH varied from 7.0 to 7.2, specific conductance varied from 497 to 498 µS/cm, and turbidity varied from 10 to 17 FNUs. All water-temperature readings were 28.5 °C during the September 14th survey. These data confirm that the stream cross section is relatively homogeneous.

Laboratory Analytical Methods

Water sample analyses were performed at the USGS Kentucky Water Science Center Sediment Laboratory. These analyses included determination of SSC from water samples collected near the turbidity probe and from composite water samples collected at the stream cross section. Sand/fine separation determinations also were made for composite samples from the stream cross section. The laboratory used the methods prescribed by Guy (1969) for the analysis of fluvial sediment concentrations and sand/fine separation. The SSC was computed according to the following formula:

$$SSC = \frac{A}{B} \times C \tag{1}$$

where:

A is the weight of sediment $\times 10^6$,

B is the weight of water-sediment mixture, and

C is the conversion factor from parts per million to milligrams per liter.

A conversion factor is required for converting concentrations from parts per million to milligrams per liter and depends on the range of the SSC.

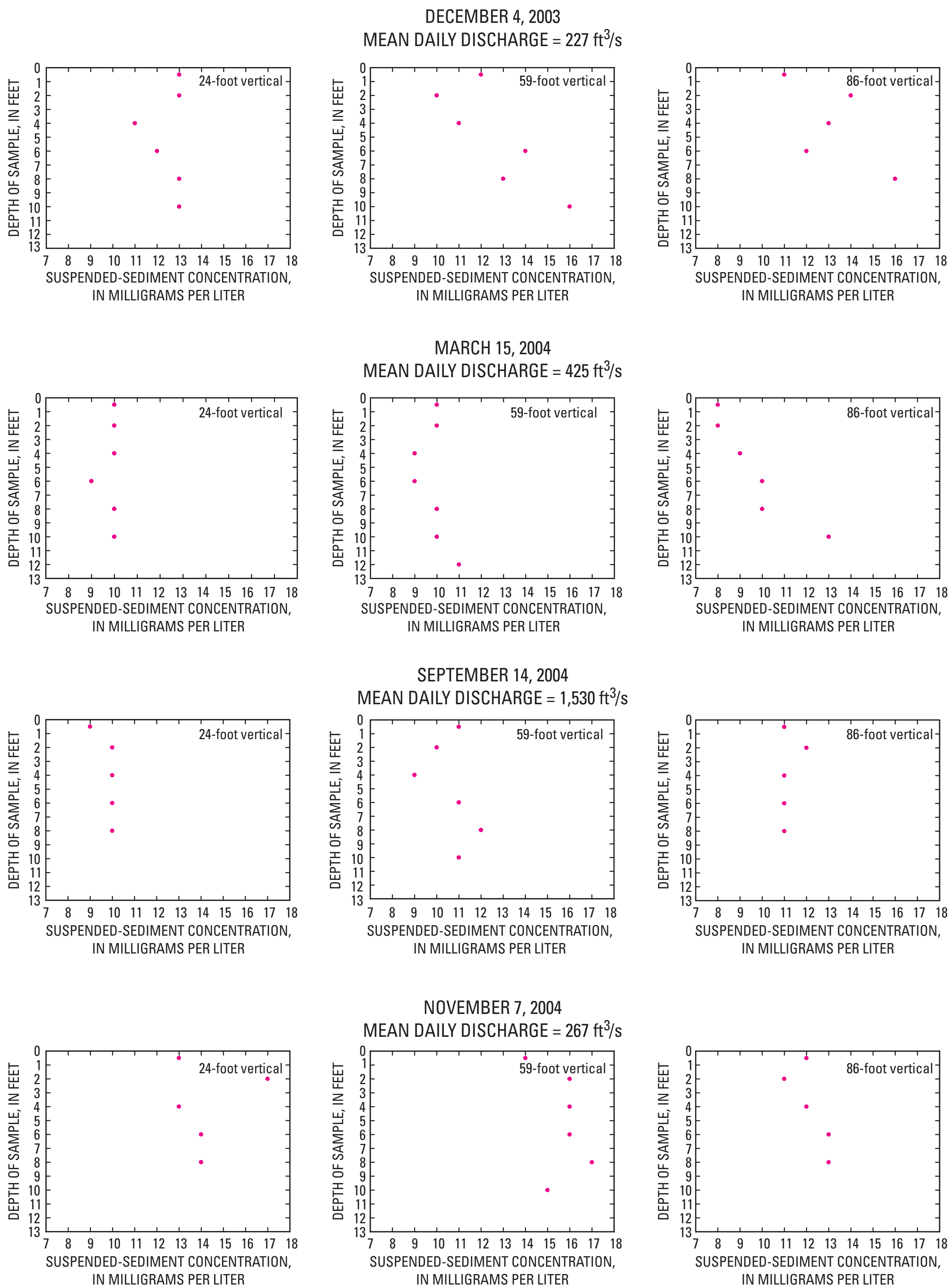

Figure 7. Suspended-sediment concentrations with depth during cross-sectional surveys at three verticals (24, 59, and 86 feet) from right bank looking downstream. Mean daily discharge shown in cubic feet per second (ft^3/s) for each cross-sectional survey.

Two alternative methods exist for the analysis of SSC—the filtration method and the evaporation method. For the current study, all water samples were analyzed by the filtration method because of the low concentrations of suspended sediment in the C-51 Canal. Each water sample was deposited in a crucible, and a vacuum was applied to force the water-sediment mixture through the filter. The crucible was then oven dried, cooled, and weighed. Mathematical adjustments for dissolved-solids concentration were not required because the dissolved solids in the sampled water passed through the filter.

The evaporation method is used when the water-sediment concentration exceeds about 10,000 mg/L, and the sediment is mostly sand, with about 200 mg/L that is mostly clay (Guy, 1969). After the water-sediment mixture is washed into the evaporation dish, the sample is dried and weighed. A correction for dissolved-solids concentration may be required when this method is used, and it is applied if the dissolved-solids concentration is greater than 200 mg/L and the sediment concentration is less than 200 mg/L (Guy, 1969).

Sand/fine separations were used to determine the amount of material that was larger or smaller than sand size. The term "fine" refers to material that passes through a 0.062-mm (0.0024-in.) mesh sieve, and "sand" refers to particles that are retained on the sieve. Wet sieve processing was used to separate the sand from the fine material. For this technique, each sieve was wetted and placed over a Pyrex evaporating dish. A sample was then washed onto the sieve with deionized water, and the screen was rinsed gently with a stream of water to wash the particles into the dish. The sieve was then thoroughly rinsed to remove any particles adhering to the sieve. Sample fractions were dried, and the gross weights of the sample fractions were electronically determined using an analytical balance and particle-size computer program.

Quality Assurance

Quality assurance was an integral part of this study, and a sampling and analysis plan was developed and approved by the FDEP prior to the collection of any samples. This sampling and analysis plan addressed issues such as project organization, description, purpose and scope, data quality objectives, selection of databases, quantitative and qualitative data quality indicators, and field and laboratory testing activities.

In accordance with FDEP requirements, quality-assurance samples were collected during the data-collection phase of this study and consisted of equipment blanks and duplicate samples. At least 5 percent of the total collected samples were quality-assurance samples. Analytical results are given below for the equipment blanks and duplicate samples collected at the probe and at the stream cross section by way of the EWI method:

Type of quality-assurance sample	Mean	Average relative percentage difference
Equipment blanks	0.00	Not applicable
Duplicate samples at probe	10.1	4.6
Duplicate samples by EWI method	8	0.00

As per FDEP requirements, analytical results for blanks should not be greater than the method detection limit (MDL). All equipment blanks were collected from the Van Dorn sampler because EWI sampling consists of placing a new bottle in the weighted sampler for each vertical for compositing. All concentrations of suspended sediment for equipment blanks were reported as 0.0 mg/L. For duplicate samples in which all values are greater than the practical quantitation limit (PQL is 4 times the MDL), the relative percentage difference (RPD) should be within 20 percent (Florida Department of Environmental Protection, 2002). The RPDs for duplicate samples collected from the probe and cross section were 4.6 and 0.0 percent, respectively. Quality-assurance data are stored in the USGS National Water Information system database and may be accessed electronically.

The USGS Kentucky Water Science Center Sediment Laboratory has an extensive quality- assurance plan that may be accessed at:

http://ky.water.usgs.gov/technical_info/dist_sedlab_files/swd_labQAPlan.pdf

This plan addresses topics such as quality assurance of sample management, laboratory equipment, computer software, laboratory apparatus, standard solutions, analytical procedures, and data management. The laboratory participates in the Sediment Laboratory Quality Assurance (SLQA) program of the Office of Water Quality, Branch of Quality Systems, and the quality assurance/quality control program developed by NASQAN.

Development of Rating Curve Estimators Using Surrogate Technology

Simple linear (ordinary least squares) and multiple linear regression analyses were used to develop rating curve estimators or models describing the relation of a response variable to single and multiple explanatory variables. Multiple linear regression analysis is an extension of simple linear regression and is used to develop relations with a response variable and multiple explanatory variables in order to explain as much of the variation in the response variable as possible, and to enhance the predictive power of the regression model or estimator. The following formula was used for simple and multiple linear regression analyses:

$$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_k x_k + \varepsilon \qquad (2)$$

where:

Y	is the response variable,
β_0	is the intercept,
β_1	is the coefficient for the first explanatory variable,
β_2	is the coefficient for the second explanatory variable,
β_k	is the coefficient for the kth explanatory variable,
x_1, x_2, x_k ...	are the explanatory variables, and
ε	is the error term.

For this study, the response variables were the SSC of depth-integrated or point samples. The explanatory variables included turbidity from the YSI 600 OMS, in formazin nephelometric units; discharge, in cubic feet per second; rainfall, in inches; and the periodic function ($\sin 2\pi T + \cos 2\pi T$) because SSC discharge may be seasonal.

Several techniques were used simultaneously to evaluate and develop rating curve estimators based on simple and multiple linear regressions. The p-values for the intercept and slope coefficients as well as the coefficients of determination (R^2) and plots that compare residuals and estimated values, response variables and estimated values, and normal quantiles and residuals were used to evaluate and choose the best model based on simple least-squares regression. The same parameters and Mallow's *Cp* statistic (discussed later) also were used to evaluate models based on multiple linear regression.

To develop the estimators, an initial assessment of the linearity between the two variables was determined using regression analysis. The R^2 values were assessed, and transformations of the response (SSC) and/or explanatory variable (turbidity) were made if greater linearity could be achieved. The p-values for the intercept and coefficients of the best models also were analyzed to determine significance at the 95-percent confidence level.

Residuals analysis was used in conjunction with p-value and R^2 value comparisons to evaluate the estimators. Residuals must be normally distributed and exhibit homoscedastic (constant) variance over the range of data values. If necessary, transformations of the response variables were used to eliminate non-normality and heteroscedastic (nonconstant) variance of the residuals. Cook's distance was used to evaluate outliers that appeared to have an inordinate influence on the regression. Based on this evaluation, data from several samples were considered erroneous and discarded; these data were presumably the result of a poor sampling technique or random fluctuations in concentrations. Helsel and Hirsch (1992) show examples of using Cook's distance in determining outliers.

Numerous approaches exist for developing and selecting a multiple linear regression model. For this study, Mallow's *Cp* statistic was used as a criterion for multiple linear regression model selection. This statistic is designed to explain as much variance in the response variable as possible by including all relevant explanatory variables, and to minimize the variance of the estimates by keeping the number of coefficients small (Helsel and Hirsch, 1992). The best model is the one with the lowest *Cp* value, which is determined as follows:

$$Cp = p + \frac{(n-p) \times (sp^2 - \sigma^2)}{\hat{\sigma}^2} \qquad (3)$$

where:

p	is the number of coefficients,
n	is the number of observations,
sp^2	is the mean square error of the model, and
$\hat{\sigma}^2$	is the best estimate of the true error.

To implement this approach, the S-Plus function drop1 was used to evaluate an initial multiple regression model that included all of the possible explanatory variables. If any of the explanatory variables exhibited a *Cp* astatistic less than the *Cp* statistic for the overall model, it was assumed not to add to the overall model improvement and was dropped from consideration (Insightful Corporation, 2001). Using this process, a "best" model with the lowest *Cp* statistic not improved by dropping any further terms was selected for the current study.

Relation of Suspended Sediment to Turbidity

As mentioned earlier, investigators have used surrogate technology based on regression analysis within the past decade to develop statistically significant models or rating curve estimators of SSC and turbidity using turbidity data from continuous instream water-quality monitoring equipment. For the current study, linear regression analysis was used to create rating curve estimators that relate SSC analyses from water samples collected at the probe and at the stream cross section (using depth and width-integrated techniques) to corresponding 15-minute turbidity readings.

The rating curve estimators, their purpose, and the associated statistics are presented in table 4. The estimators used to determine SSC at the probe and cross section using turbidity data required log transformations of response and explanatory variables to achieve greater linearity and constant residual variance. The p-values for the intercepts and coefficients were statistically significant at the 95-percent confidence level. The coefficients of determination (R^2) for the rating curve estimators for SSC at the cross section and probe using turbidity were 0.85 and 0.90, respectively, indicating that 85 and 90 percent of the variance in the response variable (SSC) can be explained by turbidity. Plots of the response variables to estimated values, residuals to estimated values, and residuals to quantiles of a standard normal distribution are shown in figure 8. Residual plots and quantile normal plots for all estimators indicate generally constant variance and normality for the residuals. The models with the most predictive power (R^2 = 0.90) include the logarithms of both turbidity and discharge as explanatory variables.

Table 4. Rating curve estimators, purposes, and associated statistics.

[*SSC*, suspended-sediment concentration; *cs*, cross section; *TRB*, turbidity; *Q*, discharge. Statistically significant at 95 percent confidence level if p-value is less than 0.05]

Rating curve estimator	Purpose	Coefficient of determination (R^2)	p-values for intercept and coefficients
$Log_{10}SSC_{cs} = 0.30 + 0.75Log_{10}TRB$	SSC estimated at cross section from turbidity	0.85	Intercept = 0.00 $Log_{10}TRB$ = 0.00
$Log_{10}SSC_{probe} = 0.19 + 0.78Log_{10}TRB$	SSC estimated at probe from turbidity	.90	Intercept = 0.00 $Log_{10}TRB$ = 0.01
$Log_{10}SSC_{cs} = 0.38 + 0.56Log_{10}TRB + 0.0001Q$	SSC estimated at cross section from turbidity and discharge	.90	Intercept = 0.00 $Log_{10}TRB$ = 0.00 Q = 0.00
$SSC_{cs} = 5.12 + 0.0063Q$	SSC estimated at cross section from discharge	.75	Intercept = 0.00 Q = 0.00

Relation of Suspended Sediment to Other Explanatory Variables

Linear regression analysis was used to develop the relation between SSC and discharge. Suspended sediment may be related to discharge through the washoff process in which rainfall results in streambank erosion, runoff from urban and agricultural areas, and the deposition of suspended materials (including sediment) in streams. The concentrations of suspended sediment determined from water samples collected by depth- and width-integrated techniques using the EWI method, as well as point samples collected at the probe, were related to the nearest instantaneous 15-minute discharge reading that was recorded during sampling.

Based on the rating curve estimator given in table 4, discharge alone explains 75 percent of the SSC variation at the stream cross section. The p-values for the intercept and discharge coefficient are all less than 0.05, indicating statistical significance at the 95-percent confidence level. The relation between SSC from water samples collected at the probe and discharge did not yield a regression model that explains much of the variation in the SSC, or that is statistically significant at the 95-percent confidence level.

These results confirm that: (1) water samples collected by means of the EWI method are more representative of suspended sediment discharged from the C-51 Canal than point samples collected at the probe; or conversely, (2) SSC samples collected at the probe do not adequately represent the suspended sediment discharged from the C-51 Canal. Examination of the residuals plot and quantile normal plot (fig. 8) did not show evidence of any nonconstant variance or non-normality of the residuals; therefore, no transformation of the response (SSC) or explanatory variable (discharge) was necessary.

To develop the best multiple linear regression model for estimating SSC at the stream cross section, the following explanatory variables were initially evaluated in the model: log turbidity, log discharge at the stream cross section, $\sin 2\pi T$, $\cos 2\pi T$, and rainfall. This model was analyzed using Mallow's *Cp* statistic and the S-Plus drop 1 function described earlier; $\sin 2\pi T$, $\cos 2\pi T$, and rainfall were dropped as explanatory variables, and log turbidity ($Log_{10}TRB$) and discharge (Q) were retained as the only explanatory variables in the best model (table 4). Rainfall had a *Cp* statistic only slightly higher than the overall model *Cp* statistic but was not included in the model because of concerns over multicollinearity considering that it is closely related to discharge. Additionally, rainfall was not statistically significant at the 95-percent confidence level with a p-value of 0.24. The p-values for the intercept and coefficients for log turbidity ($Log_{10}TRB$) and discharge (Q) were all less than 0.05, indicating statistical significance at the 95-percent confidence level. Log transformation of the response variable (SSC) was necessary due to nonconstant variance of the residuals, and a log transformation of turbidity was made to improve linearity. This model, or rating curve estimator, explains 90 percent of the SSC variance at the stream cross section. A graph showing mean daily turbidity and discharge is shown in figure 9. Both constituents generally are correlated, with the greatest turbidity usually occurring during periods of greatest discharge.

Comparison of Data for Suspended-Sediment Concentration and Transport in the C-51 Canal

Several statistical comparisons were made using data generated by the rating curve estimators (table 4). A matched pair statistical approach, involving the nonparametric Wilcoxon signed-rank test, was used to evaluate and compare the following measured values and estimated values using the rating curve estimators: (1) measured and estimated concentrations of suspended sediment, (2) estimated concentrations of suspended sediment at the probe and stream cross section, (3) estimated concentrations of suspended sediment at the stream cross section using different explanatory variables, and (4) estimated suspended-sediment loads using different explanatory variables (table 5). Continuous turbidity and discharge data collected for the 2004 water year were used to estimate the suspended-sediment concentrations in the last three comparisons.

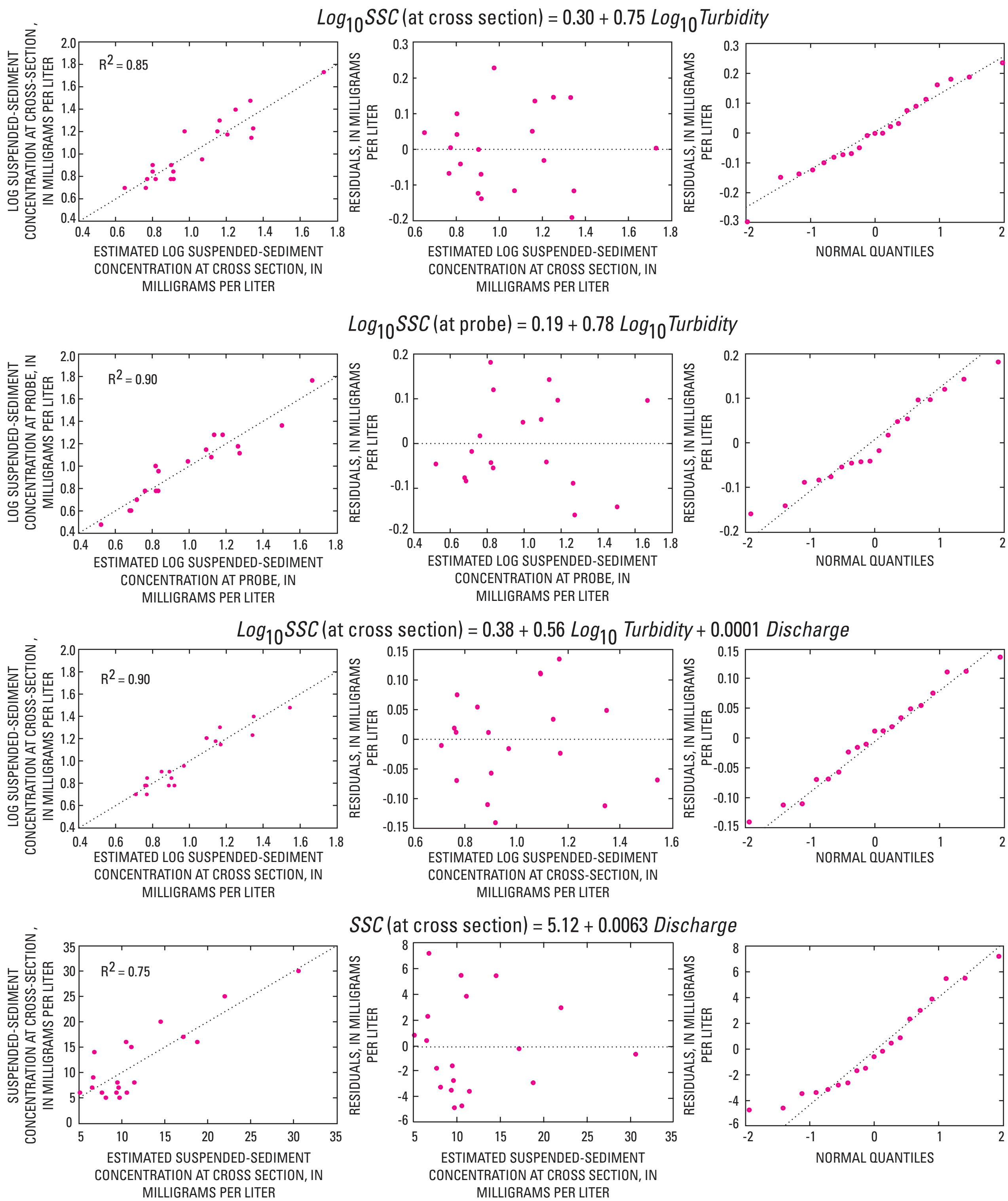

Figure 8. Comparison of response variables to estimated values, residuals to estimated values, and residuals to normal quantiles for the suspended-sediment concentration (SSC) rating curve estimators. R^2 is coefficient of determination.

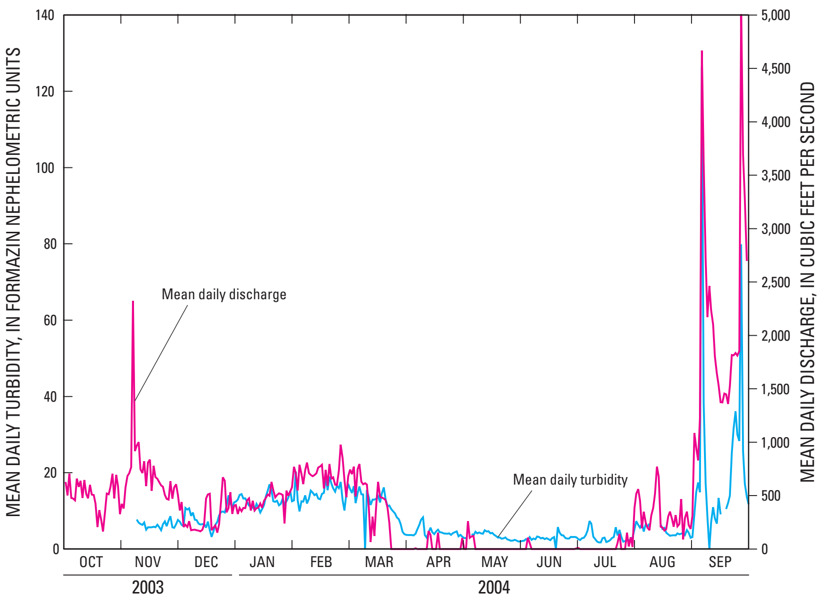

Figure 9. Mean daily turbidity and discharge for the 2004 water year (October 2003 to September 2004).

Statistically significant differences at the 95-percent confidence level (p-value less than 0.025) were found for comparisons of estimated concentrations of suspended sediment using different explanatory variables (table 5).

Differences were statistically significant between SSC estimated at the stream cross section and the probe using turbidity as the explanatory variable. Differences also were statistically significant between SSC estimated at the probe with turbidity as the explanatory variable and SSC estimated at the cross section with turbidity and discharge as the explanatory variables. All comparisons between SSC estimated at the cross section from the three rating curve estimators (table 4) that use continuous turbidity and discharge data yielded statistically significant differences (table 5); therefore, the SSC data from all three estimators come from different population distributions.

A comparison of measured and estimated mean daily concentrations of suspended sediment at the stream cross section based on the three rating curve estimators that use continuous turbidity and discharge data for the 2004 water year is shown in figure 10. The rating curve estimators, fitted values, and upper and lower 95-percent confidence limits for the concentrations of suspended sediment from the rating curve estimators are given in table 6.

Table 5. Results of statistical comparisons using the Wilcoxon signed-rank test.

[Period of record is from October 2003 to September 2004 for suspended-sediment concentrations estimated from turbidity and discharge data at the probe and cross section (*Comparison 2*), suspended-sediment concentrations estimated from turbidity and discharge data at the cross section (*Comparison 3*), and suspended-sediment loads estimated from turbidity and discharge data at the stream cross section (*Comparison 4*). Comparisons 2, 3, and 4 use continuous turbidity and discharge data. For all comparisons, the null hypothesis is the median difference of paired observations equals zero. Null hypothesis rejected at 95-percent confidence level for two-sided test if p-value is less than 0.025]

Comparison	p-value	Null hypothesis rejected (yes or no)	Comparison	p-value	Null hypothesis rejected (yes or no
Comparison 1—Measured and estimated suspended-sediment concentrations			***Comparison 2***—Suspended-sediment concentrations estimated at probe and cross section		
Measured at cross section and estimated from turbidity at cross section	1.0	no	Estimated from turbidity at probe and estimated from turbidity at cross section	.0	yes
Measured at probe and estimated from turbidity at probe	.73	no	Estimated from turbidity at probe and estimated from discharge at cross section	.67	no
Measured at cross section and estimated from turbidity and discharge at cross section	1.0	no	Estimated from turbidity at probe and estimated from turbidity and discharge at cross section	.0	yes
Measured at cross section and estimated from discharge at cross section	.58	no			
Measured at probe and measured at cross section	.54	no			
Comparison 3—Estimated suspended-sediment concentrations at cross section between explanatory variables			***Comparison 4***—Estimated suspended-sediment loads at cross section between explanatory variables		
Estimated from turbidity at cross section and estimated from discharge at cross section	.0	yes	Estimated from turbidity and estimated from discharge	.0	yes
Estimated from turbidity at cross section and estimated from turbidity and discharge at cross section	.0	yes	Estimated from turbidity and estimated from turbidity and discharge	.0	yes
Estimated from discharge at cross section and estimated from turbidity and discharge at cross section	.0	yes	Estimated from discharge and estimated from turbidity and discharge	.0	yes

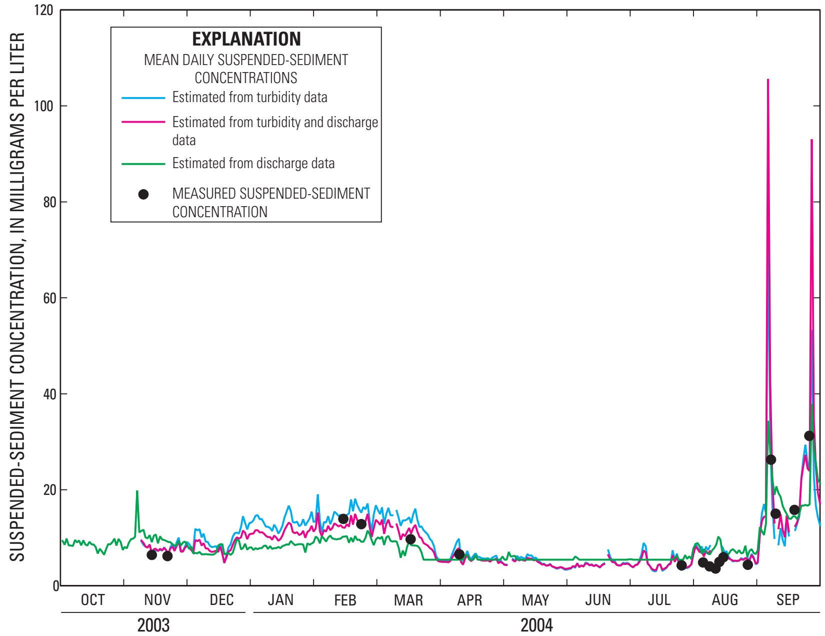

Figure 10. Measured suspended-sediment concentrations and mean daily suspended-sediment concentrations estimated using turbidity, turbidity and discharge, and discharge as explanatory variables for the 2004 water year (October 2003 to September 2004).

Table 6. Fitted suspended-sediment concentration (SSC) values and 95-percent confidence intervals from the rating curve estimators.

[*cs*, cross section; *TRB*, turbidity; *p*, probe; *Q*, discharge; LCL95, lower 95-percent confidence level; UCL95, upper 95-percent confidence level. Dash indicates no data]

$Log_{10}\ SSC_{cs} = 0.30 + 0.75 Log_{10} TRB$			$Log_{10}\ SSC_{p} = 0.19 + 0.78 Log_{10} TRB$			$Log_{10} SSC_{cs} = 0.38 + 0.56 Log_{10} TRB + 0.0001 Q$			$SSC_{cs} = 5.12 + 0.0063 Q$		
Fitted	**LCL95**	**UCL95**	**Fitted**	**LCL95**	**UCL95**	**Fitted**	**LCL95**	**UCL95**	**Fitted**	**LCL95**	**UCL95**
5.94	4.97	7.10	5.21	4.44	6.12	5.84	5.08	6.71	7.69	5.49	9.89
8.26	7.19	9.48	6.83	6.98	7.80	8.30	7.49	9.19	10.6	8.73	12.4
14.3	12.4	16.3	13.2	11.6	15.0	12.4	10.8	14.2	10.5	8.64	12.4
16.1	13.9	18.7	13.7	12.0	15.6	13.9	12.0	16.1	11.1	9.29	13.0
11.8	10.4	13.3	9.86	8.77	11.1	9.33	8.01	10.9	6.67	4.29	9.05
6.36	5.38	7.53	4.85	4.10	5.75	7.06	6.14	8.12	11.4	9.64	13.3
4.49	3.59	5.62	3.33	2.68	4.15	5.12	4.22	6.21	9.74	7.81	11.7
6.36	5.38	7.53	6.59	5.75	7.55	5.89	5.15	6.75	6.54	4.14	8.95
7.98	6.93	9.19	5.77	4.97	6.70	7.73	6.96	8.60	9.38	7.42	11.3
6.60	5.60	7.77	6.80	5.95	7.78	5.75	4.98	6.63	5.13	2.43	7.83
8.23	7.16	9.45	6.62	5.78	7.59	7.99	7.20	8.86	9.63	7.70	11.6
8.02	6.96	9.23	4.77	4.02	5.66	7.79	7.01	8.66	9.49	7.54	11.4
5.84	4.88	7.00	15.2	13.2	17.5	5.87	5.10	6.76	8.14	6.02	10.3
17.9	15.2	21.0	18.4	15.7	21.6	22.4	18.6	26.9	22.0	18.5	25.5
9.46	8.32	10.7	12.4	10.9	14.0	12.4	10.5	14.7	18.8	16.1	21.5
22.3	18.4	26.9	31.9	25.2	40.0	22.0	18.4	26.3	17.2	14.8	19.6
21.5	17.8	25.9	18.8	16.0	22.1	35.2	26.0	47.6	30.6	24.8	36.4
14.7	12.8	16.8	46.5	34.8	62.1	14.7	13.0	16.5	14.5	12.6	16.5
21.8	18.0	26.3	—	—	—	14.8	11.4	19.2	6.80	4.44	9.16
53.6	38.8	76.1	—	—	—	—	—	—	—	—	—

All comparisons of estimated suspended-sediment loads at the stream cross section from the three rating curve estimators (table 4) that use continuous turbidity and discharge data yielded statistically significant differences at the 95-percent confidence level (table 5). The estimator with the most predictive power should be employed when computing suspended-sediment loads at the stream cross section. In this case, the estimator that uses the logarithm of turbidity and discharge as explanatory variables is the best choice. Load (mass) of a constituent in streamflow is defined as the mathematical product of the concentration of the constituent (mass per unit volume) and the total volume of water passing a point (Kantrowitz and Woodham, 1994). For these comparisons, load is defined by the following equation:

$$L = SSC \times Q \times F \quad (4)$$

where:

L is load, in pounds per day;
SSC is suspended-sediment concentration, in milligrams per liter;
Q is discharge, in cubic feet per second; and
F is the conversion factor of 5.39.

A comparison of suspended-sediment loads based on the three rating curves that use continuous turbidity and discharge data for the 2004 water year is shown in figure 11.

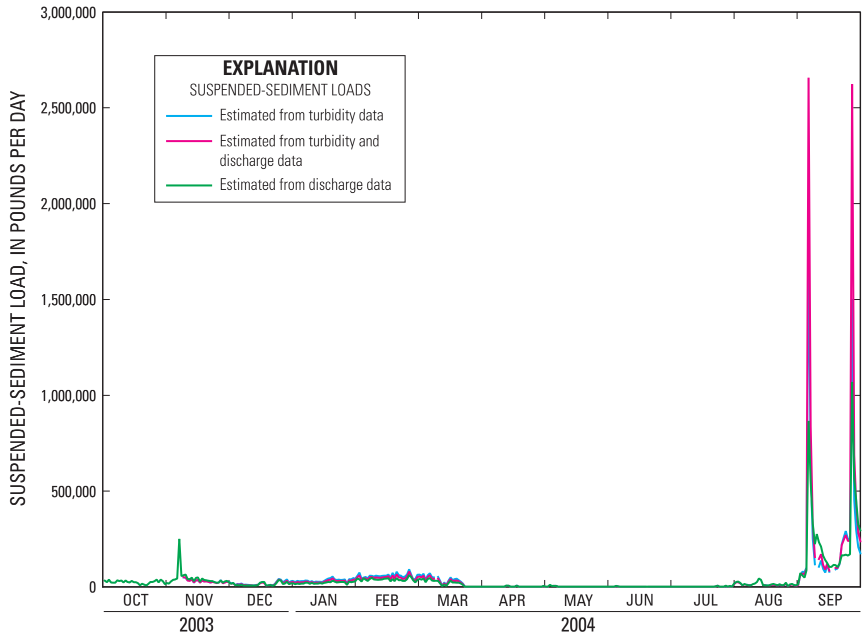

Figure 11. Suspended-sediment loads estimated using turbidity, turbidity and discharge, and discharge as explanatory variables for the 2004 water year (October 2003 to September 2004).

Summary

The Lake Worth Lagoon watershed is one of the largest estuarine lagoon habitats in Florida and encompasses more than 450 mi^2 in Palm Beach County and drains into the Lake Worth and South Lake Worth Inlets. Historically, the lagoon was a freshwater lake separated from the Atlantic Ocean by a barrier island to the east. Urbanization began in the late 19th century and has continued to the present time, resulting in considerable physical alterations to the watershed. Increased urbanization has resulted in loss of wetlands, lowered water tables, and modified runoff patterns all of which have negatively affected the natural resources and have resulted in concerns by the water-resources community over the negative effects of urbanization on water quality and aquatic life. Within the past few years, issues regarding water quality and habitat restoration have led to the establishment of the Lake Worth Lagoon Ecosystem Management Area team to identify goals and remediation efforts for lagoon restoration.

Since 1989, Palm Beach County has been involved in managing the Lake Worth Lagoon watershed. The County has identified a large area, located within the region of the C-51 Canal outflow, which contains muck sediment that is adversely affecting aquatic life and submerged aquatic vegetation. Stormwater discharged through structure S-155 along the C-51 Canal has been identified as a contributing factor in the deposition of these muck sediments. To address this problem, the U.S. Geological Survey entered into a cooperative agreement with the Palm Beach County Department of Environmental Resources Management, to investigate fluvial sediment transport in the C-51 Canal based on the use of surrogate technology.

In accordance with this study, a continuous instream water-quality monitoring device with a turbidity sensor was installed upstream of structure S-155 along the C-51 Canal in November 2003 to provide real-time turbidity data at 15-minute intervals. Twenty-seven water samples, including quality-assurance samples, were collected both at the probe location and at the stream cross section over a range of 2- to 85-percent exceedance on the flow-duration curve during various seasonal and hydrologic conditions. Data from water samples were used along with simple linear and multiple linear regression analyses to develop rating curve estimators for suspended-sediment concentration and transport; the estimators employ various explanatory variables including

turbidity and discharge. Water samples at the probe were collected using a Van Dorn sampler, and water samples from the stream cross section were collected by depth- and width-integrated techniques using the equal-width-increment method. Results of these analyses indicated that the maximum, minimum, and mean concentrations of suspended sediment at the stream cross section were 30, 5, and 12.1 mg/L, respectively. Water samples also were analyzed for sand/fine separation to ascertain the percentage of suspended sediment less than 0.063 mm or 0.0025 in. (silt and clay) in diameter. These analyses indicated that the maximum, minimum, and mean percent of sediment concentrations less than 0.063 mm in diameter were 98, 36, and 87 percent, respectively. All water samples were analyzed at the USGS Kentucky Water Science Center Sediment Laboratory in Louisville, Kentucky.

Water-quality surveys were performed at three verticals (25, 59, and 86 ft from right bank looking downstream) on December 4, 2003, March 15, 2004, September 14, 2004, and November 7, 2004, at the stream cross section to assess the degree of water-quality homogeneity within the stream. Considering the relatively low suspended-sediment concentrations, results indicated that the stream cross section was relatively homogeneous with respect to sediment concentration. The differences in suspended-sediment concentration from the three verticals ranged from 18 to 60, 11 to 62, 9 to 33, and 18 to 31 percent for the surveys made on the above respective dates. Cross-sectional surveys of pH, specific conductance, water temperature, and turbidity were made on March 11, 2004, and September 14, 2004. Respective variations for these surveys are as follows: 7.3 to 7.6 and 7.0 to 72 for pH, 678 to 682 μS/cm and 497 to 498 μS/cm for specific conductance, 4 to 20 FNUs and 10 to 17 FNUs for turbidity, and 21.6 to 22.1 °C and 28.5 °C (no variation) for water temperature.

Quality assurance was an integral part of this study and included equipment blanks and duplicate samples collected at the probe and cross section. The relative percent differences for duplicate samples collected from the probe and cross section were within the limits (4.6 and 0.0 percent, respectively) required by the Florida Department of Environmental Protection. Quality-assurance data are stored in the USGS National Water Information System database.

Four rating curve estimators for suspended-sediment concentration were developed using regression analysis. Three rating curve estimators were developed for a simple linear regression analysis, and one rating curve estimator was developed for the multiple linear regression analysis. The three rating curve estimators that were developed using the simple linear regression analysis included: (1) relation of the logarithm of suspended-sediment concentration at the cross section with the logarithm of turbidity, (2) relation of the logarithm of suspended-sediment concentration at the probe with the logarithm of turbidity, and (3) relation of suspended-sediment concentration at the cross section with discharge. Logarithmic transformations of the response and explanatory variables were made to improve the linear relation and to compensate for heteroscedastic (nonconstant) variance of the residuals. The multiple linear regression analysis was used in the development of the rating curve estimator that relates the logarithm of suspended-sediment concentration at the cross section with the logarithm of turbidity and discharge. The criterion for best model selection was the lowest Mallow's *Cp*. This statistic is an overall measure of model adequacy that: (1) explains as much variance in the response variable as possible by including all relevant variables, and (2) minimizes the variance of the estimates by keeping the number of coefficients small. The coefficients of determination (R^2) for the models ranged from 0.75 to 0.90. The models with the most predictive power ($R^2 = 0.90$) utilize both the logarithm of turbidity and discharge as explanatory variables.

A matched pair statistical approach was employed to make comparisons at the 95-percent confidence level with measured data values and data estimated from the various estimators using the nonparametric Wilcoxon signed-rank test. Statistical comparisons were made between measured suspended-sediment concentrations and suspended-sediment concentrations estimated at the stream cross section and probe from each of the four rating curve estimators that use continuous turbidity and discharge data. No significant differences occurred at the 95-percent confidence levels for two-sided tests because the p-values were all greater than 0.025. There were statistically significant differences, however, at the 95-percent confidence level for the comparison between suspended-sediment concentrations estimated at the probe and at the cross section using turbidity alone as the explanatory variable and for the comparison between suspended-sediment concentration estimated at the probe from turbidity alone and at the cross section from both turbidity and discharge. Statistical comparisons of suspended-sediment concentrations and loads estimated at the stream cross section for the 2004 water year, using continuous turbidity and discharge data for the three rating curve estimators, showed statistically significant differences at the 95-percent confidence level. Therefore, when computing suspended-sediment concentrations and loads, the estimator with the most predictive power should be used which in this case, is the one employing logarithm of turbidity and discharge as explanatory variables.

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